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Back-analysis of the collapse of the Clamart chalk underground quarry – Paris (France)

Rétro-analyse de l'effondrement de la carrière de Clamart – Paris (France)

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ABSTRACT Many large collapses have occurred during or after underground quarry operations. The collapse of the Clamart underground quarry (in 1961, South of Paris-France) is well known as one of the most catastrophic. This paper presents a back-analysis of the case study using an empirical approach. Based on a set of assumptions, the empirical approach has indicated a reliable scenario that may explain the collapse: the large collapse may have been caused by a lack of bearing capacity of the pillars and the sudden failure of a hard limestone bed in the roof, the load on which would have been concentrated until overload occurred. The bed weakness between the two quarrying levels may also have had an influence on the general lack of stability of the quarry. Moreover, under the given hypothesis, the study shows a very low influence of the water table due to flooding of the underground quarry.

RÉSUMÉ Les effondrements peuvent affecter les cavités souterraines pendant et après le creusement. L'effondrement historique en 1961 de la carrière de Clamart (sud de Paris – France) est connu comme le plus catastrophique. Cet article présente une rétro-analyse basée sur une approche analytique-empirique. Les résultats ont montré que la cause principale de l'effondrement est l'insuffisance de la résistance des piliers et la rupture brutale du banc de calcaire du haut toit. Les piliers ont été stables grâce à la présence du banc de calcaire dans le toit. D'autres facteurs comme l'envoyage et la rupture de l'intercalaire ont également contribué à l'effondrement, avec un rôle moins important.

1 INTRODUCTION AND OBJECTIVES

Man-made and natural shallow cavities have caused many different problems with geohazard, and sometimes large collapses. In France and around the world, the old quarries were often excavated using the room and pillar method (Figure 1). This method results in substantial geohazard long after the underground quarry has been abandoned and therefore poses a serious public safety issue today (Gutiérrez et al., 2009). Shallow man-made chalk cavities (depth < 50 m) can be affected both by local collapses and large collapses (Vachat, 1982, Kaufmann and Quinif, 2002, Gilbride et al., 2005, Edmonds, 2008). The impact of collapse on the surface can be subsidence or sinkholes. Such collapses can be found in the literature (Bell et al., 2005). A large collapse covers a

large surface and can culminate in a small earthquake or rockburst; in one gypsum underground quarry, the local magnitude was registered at near 3.1 (Wang et al., 2008).

In France, there are about 150,000 known quarries, and many of them are located in the chalk, limestone and gypsum of the sedimentary Paris Basin (Gombert et al., 2013).

Chalk is a white and soft limestone which forms the base of the Parisian sedimentary basin. The chalk was extensively underground quarry until the beginning of the 20th century. The room and pillar mining method was used to protect the surface of the land and to ensure the long-term stability of the pillars. However, the long-term stability is never guarantee, and 391 subsidence events related to underground man-made cavities were recorded from 1977 to 2000.

of which employed a room and pillar method. Different extraction ratios were followed; the galleries on the upper level were about 7 meters high in both the northern and southern zones. The pillars between the two zones were irregular in shape, showing a hybrid design (Figure 4).

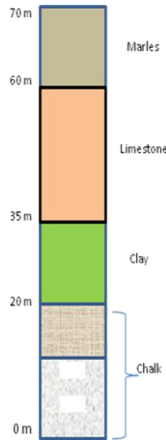


Figure 4. Simplified cross-section of the overburden chalk underground quarry.

The rooms on the lower level were about 4 metres high and existed only in the southern part, as shown in Figure 5. On the two levels, the area between the northern and southern zones was probably situated on a property line. The interlayer bed (immediate roof of the lower level) was about 4 metres high, and the two levels were perfectly superimposed. The geometrical characteristics of the different underground quarry areas shown in Figure 5 can be found in Table 1. The extraction rate ranges from 36% to 68%. The pillar width/height ratio varies between 0.75 and 1.4.

Table 1. Geometrical characteristics of the upper and lower levels.

Zone	Pillar shape	Pillar dimensions (l*L m)	Gallery dimension (W*H m)	Extraction ratio %
ZSS1	Rect.	7*9-15	7	57
ZSS2	Hybrid	5*5	4*7	55
ZNS1	Square	7*23-27	4*6.8	68
ZSI1	Rect.	7*18	4*5	45
ZSI2	Rect.	7*14	4*5	51
ZSI3	Irreg.	-	4*5	36

3.1 Objective

Various experts have attempted to explain the collapse between 1961 and 1979 on the basis of in-situ

observations. The causes leading to the collapse have not yet been fully explained, although several hypotheses have been proposed in reports and articles dealing with this disaster.

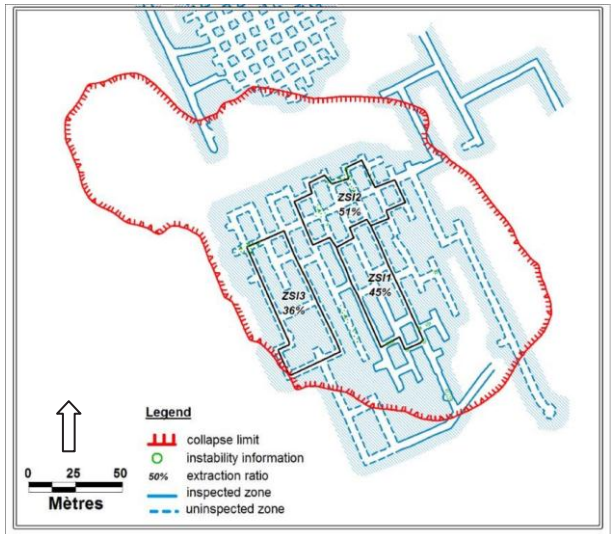
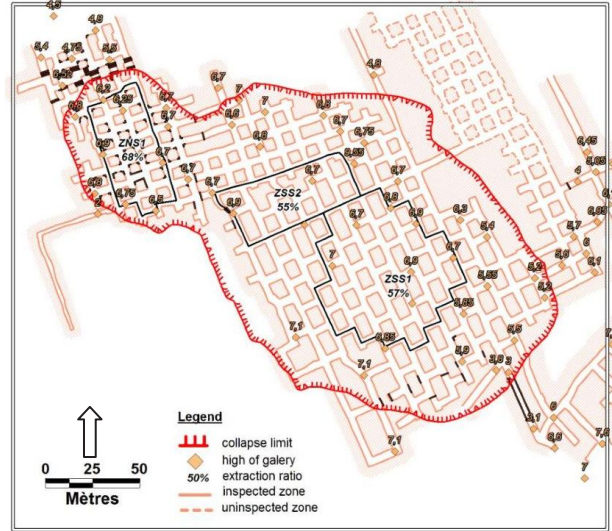


Figure 5. The upper and lower levels of the underground quarry (left and right, respectively, from IGC report).

IGC considered the main cause of the collapse was the failure of the limestone bed located on the upper roof (unpublished expert reports from 1961, 1976). Maury (Maury, 1979) considered the main factor of the collapse to be the hydraulic load and water pressure induced by rain many days before the collapse.

The aim of this article is to allow a better understanding of the origin of the collapse through an evaluation of the stability of the underground quarry and an analysis of triggering factors and their associated failure mechanisms.

4 ASSESSMENT OF UNDERGROUND QUARRY INSTABILITY

From the date of the collapse up to now, several communications by experts and authorities attempted to explain the collapse of the Clamart underground quarry (Maury, 1979). They considered the explosion, slipping of the limestone layer on the plastic clays, weak pillars under the water level, hydraulic pressure in the cover layers after previous pipe leaks or heavy rain. To this day, it remains difficult to determine the real cause of the instability. In order to achieve the objective, the adopted methodology is divided into two parts; the first part concerns the stability of the underground quarry before the collapse, while the second part concerns the triggering factors. An empirical-analytical approach was used in parallel to identify the relevant causes of the catastrophic collapse.

In order to assess the stability, a main hypothesis is made: the large collapse of the underground quarry is supposed to have been initiated by the failure of the pillars in the area where there is the deepest subsidence and where the extraction ratio is near the maximum. This corresponds to the area in which the two levels are superposed. The collapse of the pillars could be induced by secondary factors: collapse of the immediate roof, hard limestone bed and water, and underground quarry flooding.

4.1 Assessment of pillar stress

The analytical-empirical approach allows for the successful design and the stability assessment of the underground quarry, depending on the individual pillar stability (Bekendam, 2004). The average pillar stress can be estimated by the tributary area method based on the following parameters for the geometry of rooms and pillars, the depth and the specific weight of overlying rocks. The method was applied to the Clamart zones (Table 2).

Table 2. Pillar vertical stress calculated by the tributary area method for each zone from Figure 5 (safety factor was calculated for unconfined compression strength equal to 2.1 MPa)

Zone	τ (%)	D (m)	γ (t/m ³)	σ_p (MPa)	F
ZSS1	57	42		1.95	1.07
ZSS2	55	42		1.87	1.12
ZSI1	45	52	2	<u>1.75</u>	<u>1.20</u>
ZSI2	51	52		1.96	1.07
ZSI3	36	52		1.50	1.40
ZNSI	68	35		2.19	0.96

τ : extraction ratio, D: depth, γ : density, σ_p : pillar stress, F: safety factor

The minimum pillar stress calculated out of the 6 zones of interest is 1.75 MPa (Zone ZSS1 on Figure 5). This corresponds to the area of maximum subsidence, thus reinforcing the initial hypothesis of the initiation of the collapse.

Pillar failure occurs when the pillar is loaded beyond its bearing capacity and the safety factor is less than 1. A large-scale collapse can occur as a catastrophic collapse when an excessive convergence exists; the slenderer the pillar is, the wider the area of collapse is (Esterhuizen et al., 2006). The pillar bearing capacity was first assumed to be the same as the chalk's unconfined compression strength (UCS). This was possible thanks to the compression testing that had been conducted (with different values of water content) just after the collapse (in June 1961) and resulting in Table 3. We adopted the weakest value of compression strength (2.1 MPa) for the collapse analysis.

A simple comparison between the unconfined compression strength and the pillar stress indicates that the pillars should not have collapsed, except for ZNS1 (factor of safety <1). However, the subsidence of the surface above the ZNS1 was less than in other zones. In addition, it is known that laboratory strength does not take the large-scale effect into account, so the pillar strength is in fact lower than the laboratory strength. The compression strength of the chalk on a large scale has been estimated at 1.9 MPa based on laboratory tests and back-analysis on the region's chalk underground quarries in the Paris region (Watelet, 1996). And yet it is still too high to explain the collapse.

Table 3. Unconfined compression strength (UCS) characteristics of the Clamart chalk underground quarry (IGC, 1961, unpublished) for different values of water content (W)

W	UCS (MPa)	UCS av. (MPa)
50%	5.6; 3.5; 3.4	4.17
65%	5.0; 2.8; 2.5	3.43
83%	3.2; 2.0; 2.4;	2.53
90%	2.7; 2.5; 2.0	2.4
Immersion for 3 weeks	2.1	2.1

According to our observations and the known relationship between the underground quarry opening and the subsidence, the maximum subsidence was located in ZSI1 (Figure 5); one can assume that the collapse of the pillars started there. In order to have an idea of the pillars' strength, we assume the factor of safety (FoS) of zone ZSI1 (lower level) to be 1. It must be noted that the safety factor may have been lower (meaning a lower strength of the pillars), but the underground quarry stabilized temporarily for an unknown reason (the resistant limestone roof and/or the local confining pillars by backfilling). Anyhow, given that the pillars were doubtlessly unstable (since they eventually collapsed), the safety factor is 1 at the most and the ultimate strength of the pillars is 1.75 MPa. Considering this value as the failure criterion:

- the failure criterion is exceeded in zones ZSS1, ZSS2, ZSI2, all of which also collapsed;
- the failure criterion is not reached in zone ZSI3, which is still standing;
- the failure criterion is far exceeded in zone ZNS.

This zone has not collapsed, probably because of the reinforcement on the pillars observed in this area. This probably means that they were showing signs of instability and consequently reinforced.

However, it must be noted that, before the collapse, the upper level showed no disorders due to overloading (no fissures and cracks) and had never been treated by any reinforcement (IGC, 1961). This is inconsistent with the instability of the pillars of ZNS1 and ZNS2, unless no existing disorders were observed in the chalk. Indeed, signs of instability are known to be difficult to see in chalk. It follows logically, however, that they should have been noticed the same way that damage was noticed in area ZNS.

4.2 Hydrogeological context of the 1961 event

May water be considered as one instability factor that led to the collapse? The underground quarry collapse occurred when the chalk water table was at an average or moderately high level, following 15 years of low water table. The lower underground quarry level had probably already been flooded for a long time after the abandonment of the Clamart underground quarry (1880).

Concerning the hydrological context, the level of the Seine can vary from a minimum of around 26 m a.s.l. (inducing chalk drainage) to a maximum of 35 m a.s.l. (inducing chalk recharge). The Seine level might have been low (around 27 m a.s.l.) during the months preceding the event.

In terms of rainfall, 1961 was a dry year (540 mm) following a rainy one (>700 mm in 1958 and 1960). Looking at a monthly scale, May 1961 is one of the rainiest months of the 1941-1960 period. It is mainly characterized by heavy rainfalls concentrated on a small number of days. Other potentially aggravating factors related to water were recorded shortly before the collapse:

- earthworks were underway in eastern edge of the football stadium and caused the rupture of a water pipe, releasing about 100 m³ of water above the mining area within 2 hours;
- mishandling occurred at the drain valve sprinkler system of the stadium, located in the northwest end; this resulted in the spillage of 2500 m³ of water during the first 3 weeks of March.

The global hydrogeology context of the 1961 event can be summarized as follows:

- the chalk aquifer water table was average since the beginning of the year;
- the Seine had already begun its summer low flow and low level period;
- the rainfall was characterized by a dry first semester followed by a very rainy last week of May, the week preceding the event.

5 CONCLUSION

The main objective of this back-analysis of the large collapse of the Clamart chalk underground quarry was to identify and to understand the origins of the

tragic event in order to predict such events for identical configurations. The back-analysis indicates that the chalk underground quarry was, before the collapse, very close to its ultimate strength and collapse.

The empirical-analytical approach indicates that the strength of chalk must be more than 1.75 MPa (the pillar stress) for stable pillars; the underground quarry may be unstable because the laboratory tests and site effect indicate that the strength is very close to the actual pillar stress.

Therefore, the scenario of the large underground quarry collapse probably occurred in the upper pillars. However, no damage was observed on the upper pillars despite being close to the ultimate load. This puts forward the role of the resistant limestone bed (Figure 4): it would have taken back the overload, preventing pillar damage, and it then would have lost its stiffness, leading to the overloading of the pillars and the collapse of the underground quarry. The causes of the limestone bed failure may be multiple origins: hydraulic overload fracture, progressive deterioration of the bonds to the minimal recovery due to the water, and local failure of a pillar sufficiently increasing the overload on the roof.

The bed between the two chalk levels may have fallen during the general collapse, explaining an observed collapse on two levels and affecting the strength of the pillars.

The scenario explaining the breakdown of the upper pillars only concerns the fall and the resumption of stresses through the roof. It does not examine the failure mechanisms in the roof. The presence of two exploitation levels has some importance, but the main role concerns the weakness of the chalk layer and the existence of the hard bed in the overburden.

The methodology developed in this paper uses a scientific and operational approach to explain the causes of such phenomena and to identify the role of different factors suspected by experts. The back-analysis and the knowledge of local context put together are very useful for the understanding of the complex geotechnical phenomena.

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